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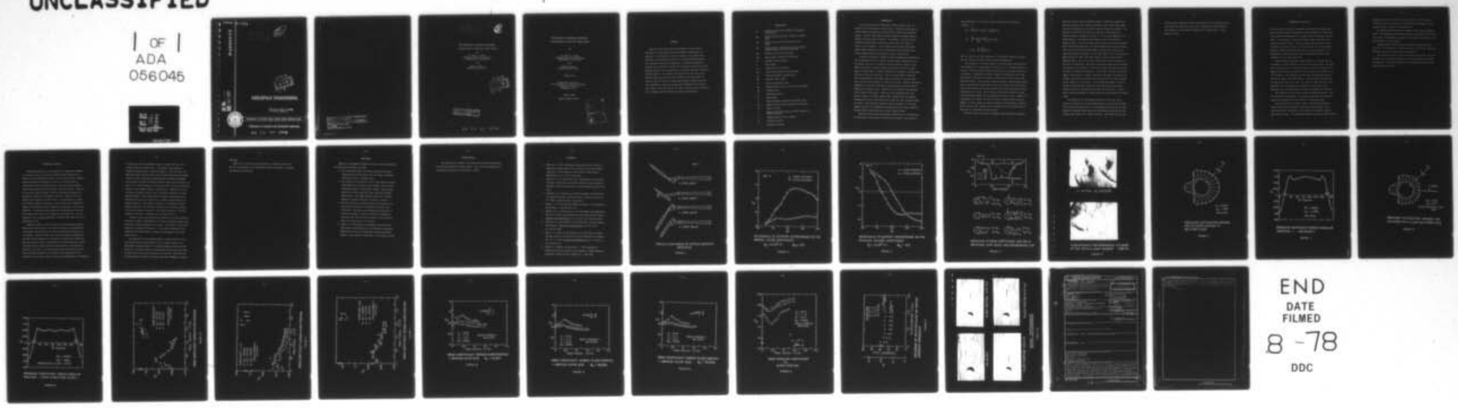

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THE INFLUENCE OF AERODYNAMIC INTERFERENCE ON HIGH ANGLE OF ATTACK WIND TUNNEL TESTING

by

Dr. Robert C. Nelson
Assistant Professor of Aerospace
and Mechanical Engineering

and

Thomas N. Mouch
Second Lieutenant USAF

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Prepared for

United States Air Force
Air Force Office of Scientific Research
Bolling Air Force Base
Washington, D.C.

June 6, 1978.

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ABSTRACT

Results from an experimental investigation of strut support interference on high angle of attack aerodynamic measurements are presented. The influence of the strut support on the leeward wake structure was investigated by means of a two-dimensional experiment of a cylinder-splitter plate combination. Pressure distributions, pressure drag coefficient and wake flow visualization data for various cylinder-splitter plate combinations are presented for high subcritical Reynolds numbers. The influence of plate position and size on the pressure drag coefficient were also examined. The results show the splitter plate can alter the vortex wake formation significantly and, as a consequence, reduce the pressure drag coefficient by as much as 30% or more. Plate sizes of 0.5, 1.1 and 1.5 diameter were tested with the 1.1 diameter plate yielding the largest drag reduction.

NOMENCLATURE

C_D	Cylinder pressure drag coefficient (drag/unit length)/$(q_\infty D)$.
C_{D_c}	Crossflow drag coefficient (drag/unit length)/$(q_\infty D)$.
C_N	Normal force coefficient (normal force)/$(q_\infty S)$.
C_M	Pitching moment coefficient (pitching moment)/$(q_\infty SD)$, measured about body mid-point.
C_P	Pressure coefficient $(P_S-P_O)/q_\infty$.
C_{P_b}	Base pressure coefficient $(P_S-P_O)/q_\infty$.
D	Cylinder or body diameter.
ℓ	Body length.
P_o	Freestream static pressure.
P_s	Local static pressure on the cylinder.
q_∞	Freestream dynamic pressure $\frac{1}{2}\rho\ U_\infty^2$.
R_e	Reynolds number, $u_\infty D/\nu$.
S	Body cross-sectional area.
S_b	Cross-sectional area at the base of the missile.
S_p	Planform area.
u_∞	Freestream velocity.
V	Body volume.
X	Distance between cylinder and splitter plate.
X_m	Moment reference center measured from the nose.
α	Angle of attack.
η	Ratio of drag coefficients of finite cylinder to infinite cylinder.
θ	Azimuth position on the cylinder.
ρ_∞	Freestream density.
ν	Kinematic viscosity.

INTRODUCTION

In recent years we have witnessed a radical change in what is referred to as high angle of attack flight. Previously, high angle of attack flight would have been characterized as angles approaching 30 degrees. However, many modern aerospace vehicles are being tested at angles far greater than 30 degrees. For example, a certain class of thrust-vector-controlled missiles have been tested for angles of attack up to 180 degrees. In the subsonic and transonic Mach number range various anomalies occur in the measured force and moment data. These anomalies have been attributed to support interference.

To perform aerodynamic testing on slender aerodynamic configurations over a wide angle of attack regime, various support combinations (e.g. aft sting, strut or nose sting) are usually required. Figure 1 shows some of the types of support systems that might be used in the high angle of attack region. Support interference, in general, is quite small for most of the test conditions. That is, the mis-match in measured force coefficients at overlapping angles of attack for the aft sting, strut and nose sting supports is usually quite small. However, noticeable differences in the force and moment coefficients have been observed in subsonic and transonic flows. Figures 2 and 3 illustrate the magnitude of the support interference. These data were obtained by Dietz and Alstatt, using a 10 caliber tangent ogive cylinder model. The largest discrepancies occur in the normal force coefficient near 90 degrees angle of attack. Their data also indicates that the influence of the sting support system on the aerodynamic measurements is quite small compared to the interference associated with the strut support system.

The normal force and pitching moment coefficients of a slender body of revolution at large angle of attack can be related to the crossflow drag coefficient of an infinite cylinder by means of the following formulas: [1,3]

$$C_N = \frac{S_b}{S} \sin 2\alpha \cos \frac{\alpha}{2} + \eta\, C_{D_c} \frac{S_p}{S} \sin^2\alpha$$

$$C_M = \left[\frac{V - S_b (\ell - X_m)}{SD}\right] \sin 2\alpha \cos \frac{\alpha}{2}$$

$$+ \eta\, C_{D_c} \frac{S_p}{S} \frac{X_m - \bar{X}}{D} \sin^2\alpha$$

The first term in the above equations is the familiar slender body result and the second term is the viscous crossflow contribution.

The influence of the strut support on the aerodynamic characteristics of a slender body at large angles of attack may act in a manner similar to that of a wake splitter plate located downstream of an infinite cylinder in a crossflow. Experiments by Roshko[4], Bearman[5], Gerrard[6] and Apelt, West and Szewczyk[7] examined the influence of wake splitter plates on the flow past bluff bodies. The collective results from these investigations showed that a splitter plate placed parallel with the cylinder axis and the free-stream could obstruct the vortex formation and lessen the extreme reduction in pressure in the wake. Most of these tests were performed at low sub-critical Reynolds numbers for Mach numbers less than M = 0.44. Roshko did investigate the effect of the splitter plate at super-critical Reynolds numbers. In this region, the plate was found to be ineffective, primarily due to the fact that the wake is not characterized by the dominate vortex flows but by a disorganized turbulent wake.

The flow around a cylinder is extremely complicated and is dependent upon the crossflow Mach and Reynolds numbers. Additional insight into the flow patterns around circular cylinders in the critical Mach number range are highlighted in the paper by Nauman, Morsbach and Kramer[9]. The variation in drag and wake flows as a function of Mach number and Reynolds number is presented in Figure 4. For the curve marked by the Roman numeral I, the critical Mach number occurs at a subcritical Reynolds number. Local shock waves develop, which prevent the separation point from moving downstream, even when boundary layer becomes turbulent. Thus, when the critical Reynolds number is reached, the flow pattern remains essentially unchanged. On the other hand, on the curve marked by Roman numeral II, the critical Mach number occurs at super-critical Reynolds number. Now, in this case, the boundary layer is turbulent at the point of separation. Once again, shock waves develop on the cylinder and, because of the pressure rise across the shock, the separation point is fixed at a smaller azimuth angle. As a result, the wake is wider and again a vortex street is formed. The local shock waves occurring on the cylinder were found to alternate from side to side at the same frequency as the shedding of the vortices. As the higher Mach number flow has a distinct vortex wake, the influence of the splitter plate may again become effective in reducing the crossflow drag coefficient. Figure 5 shows several photographs of the wake patterns for the higher Mach number flows.

The purpose of the investigation reported in this paper was to examine the influence of a wake splitter plate on the pressure distribution and wake characteristics of a two-dimensional cylinder in the high subcritical Reynolds number regime for Mach numbers above and below the critical Mach number for a circular cylinder. The results for the subcritical Mach and Reynolds numbers are presented in the following section. It is hoped that these data can be used to improve the understanding of the influence of strut support interference on slender models at large angles of attack.

EXPERIMENTAL FACILITIES

All tests and data from the investigation reported in this paper were made in the Notre Dame low-turbulence subsonic wind tunnel. The tunnel is an indraft tunnel powered by a variable speed 15 horsepower electric motor. Low turbulence is achieved by using a large contraction ratio and anti-turbulence screen. There are twelve anti-turbulence screens preceding the reduction cone. The first seven are 14 x 18 mess bronze screens, followed by five 20 mesh screens of nylon marquisette. The combination of large contraction and anti-turbulence screens yields turbulence levels of less than 0.2%.

A hollow aluminum cylinder, having a length (24 inches /61 cm) to diameter(2 inches /5.08 cm) of 12 was used in these tests. The model had 22 pressure taps; 16 of the taps were located at the center of the model and were positioned from -30° to 195° around the circumference in 15° increments. The remaining 6 pressure taps were located along the span of the model at the 180° position. These pressure taps were used to check the quality of the flow, i.e. check for "wash-out" due to the boundary layer. By examining the pressure on these 6 taps it was determined that end plates were not needed to eliminate any "wash-out".

The roughness of the cylinder, though not measured exactly, could be considered as very smooth. To ensure a smooth finish the model was center-less ground prior to the start of the testing program.

The splitter plate was made of steel. Aluminum was originally chosen but was found to flutter in the wake of the cylinder, even at very slow speeds. Using steel, this problem was eliminated except at the very high speeds. The plates were designed to span the tunnel and had dimensions of 1/4: x 1" (0.64 cm x 2.54 cm), 1/4" x 2.25" (0.64 cm x 5.72 cm) and 1/4" x 3" (0.64 cm x 7.62 cm) which corresponds to plate lengths of 0.5D, 1.1D and 1.5D, respectively.

All pressure distributions were measured, using a 36-tap manometer board. The manometer was filled with unity oil and slanted at 30^{o} to the horizontal. This manometer is graded in millimeters, thus giving a very fine resolution to any readings.

Reynolds number variations were achieved by varying the tunnel velocity. The velocities of 45 fps/13.9 m/sec, 69.5 fps/21.4 m/sec and 85 fps/26.2 m/sec were used in this investigation.

With the model in place, the area blockage ratio was 8%. For this blockage ratio only small corrections to the measured drag coefficient are required. The results presented in the following section are the uncorrected measured data.

DISCUSSION OF RESULTS

The primary objective of this study was to examine the influence of a splitter plate on the wake and pressure drag coefficient of a right circular cylinder placed normal to the flow direction. Figure 6 shows the pressure distribution in terms of the local pressure coefficient without the splitter plate. After the laminar boundary layer separates,the pressure coefficient increases slightly. This can be seen more clearly in Figure 7 where the pressure distribution is plotted as a function of the angular position. Figures 8 and 9 are similar plots; however, for these cases, a splitter plate is located 0.53 diameters behind the cylinder. These figures show a significant change in the leeward pressure coefficient as compared to the no plate condition. The splitter plate lessens the extreme pressure reduction in the wake, which results in a substantial drag reduction. For this particular case, the drag coefficient is reduced from 1.088 to 0.811 or approximately 25%.

Figures 10, 11 and 12 show the effect of varying Reynolds numbers, holding plate size constant. All three plates show a pronounced drop in the drag coefficient once the plate is introduced and abutted on to the cylinder. With each plate size a distinct region was found where the plate became ineffective in reducing the cylinder drag coefficient. Near this critical point a slight variation in plate position can cause the flow regime to switch from the low drag profile to the high drag profile or vice versa. For the two larger plates (1.1D and 1.5D), the drag coefficient decreases as the plate is moved downstream of the cylinder, until the plate reaches a position of approximately 2.5 diameters.

At this point, the drag suddenly returns to a value similar to the cylinder without a splitter plate. The smallest plate exhibits a somewhat different trend, as noted in Figure 10. For this case, the drag coefficient increases as the plate is moved away from the cylinder until it reaches a position of approximately 0.6 diameter downstream. At this point, the drag coefficient decreases until the plate reaches an X/D of 1.8. Further movement of the plate results in a drag coefficient similar to the cylinder without a splitter plate. Figures 13, 14 and 15 show the influence of plate size on the drag coefficient for fixed Reynolds numbers. These figures show the amount of drag reduction is dependent upon plate size, with the 1.1 diameter plate producing the largest reduction. This result is similar to the findings of Apelt, West and Szewczyk[7]. The influence of plate size on the base pressure coefficient is shown in Figure 16. The largest reduction in the base pressure coefficient is caused by the 1.1D splitter plate.

As noted earlier, the splitter plate inhibits the vortex formation around the cylinder. Measurements of the vortex shedding frequency were made with a single component hot wire probe. The results of this investigation are presented in Figure 17. As the figure illustrates, the frequency or Strouhal number is reduced by the presences of the wake splitter plate.

The reduction in the drag coefficient is a direct result of the vortex wake pattern being inhibited. This is shown clearly in the photographs comprising Figure 18. The first photograph shows the wake pattern for a cylinder without a splitter plate and the next three show the wake pattern for various splitter plate locations. With the plate located immediately behind the cylinder, the vortex shedding is clearly inhibited.

Note that, as the plate is moved beyond 2.5 diameters, the vortex pattern re-establishes itself immediately behind the cylinder, as though the plate were not present.

CONCLUSIONS

Based on the experiments performed as part of this investigation, the following conclusions were drawn:

1. The wake splitter plate was found to reduce the pressure drag coefficient sufficiently, with the largest reductions occurring for the 1.1 diameter plate.
2. The influence of the splitter plate on the cylinder pressure drag coefficient was found to vary slightly over the range of Reynolds numbers tested, 45,000 - 83,000. High Reynolds numbers were tested; however, flutter problems developed with splitter. The higher Reynolds number data, 150,000, exhibited a similar trend until the onset of flutter.
3. With each plate size a distinct region was found where the plate became ineffective in reducing the cylinder drag coefficient. Near this critical point small movements of the plate position in either the upstream or downstream directions were found to cause the wake to switch from the high to low drag profile or vice versa.
4. Finally, the two-dimensional experiments reported in this paper provide some insight into the complicated aerodynamic interference that may be present when testing aerodynamic models at large angles of attack with a strut support system.

ACKNOWLEDGEMENT

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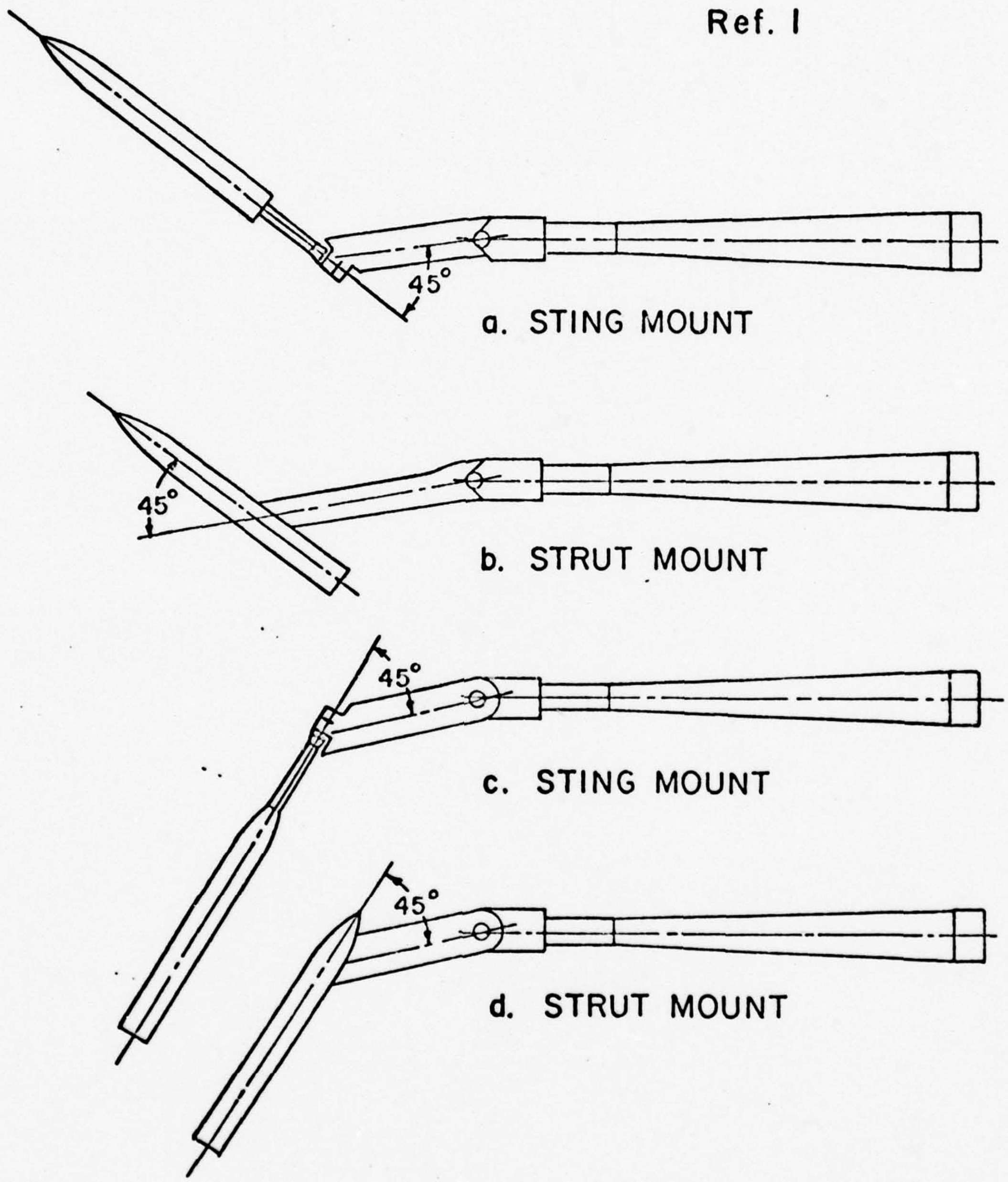
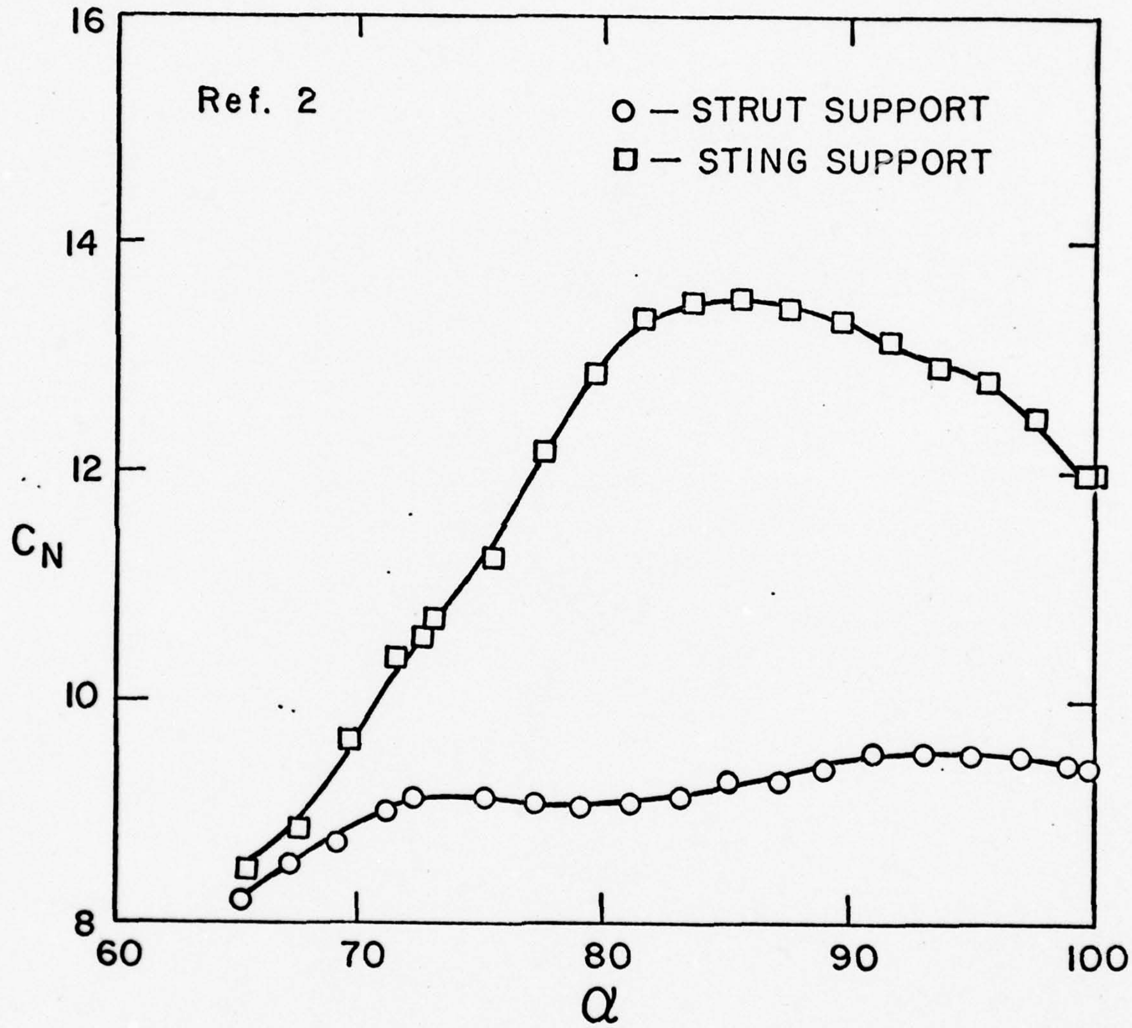
Ref. I



TYPICAL HIGH ANGLE OF ATTACK SUPPORT SYSTEMS

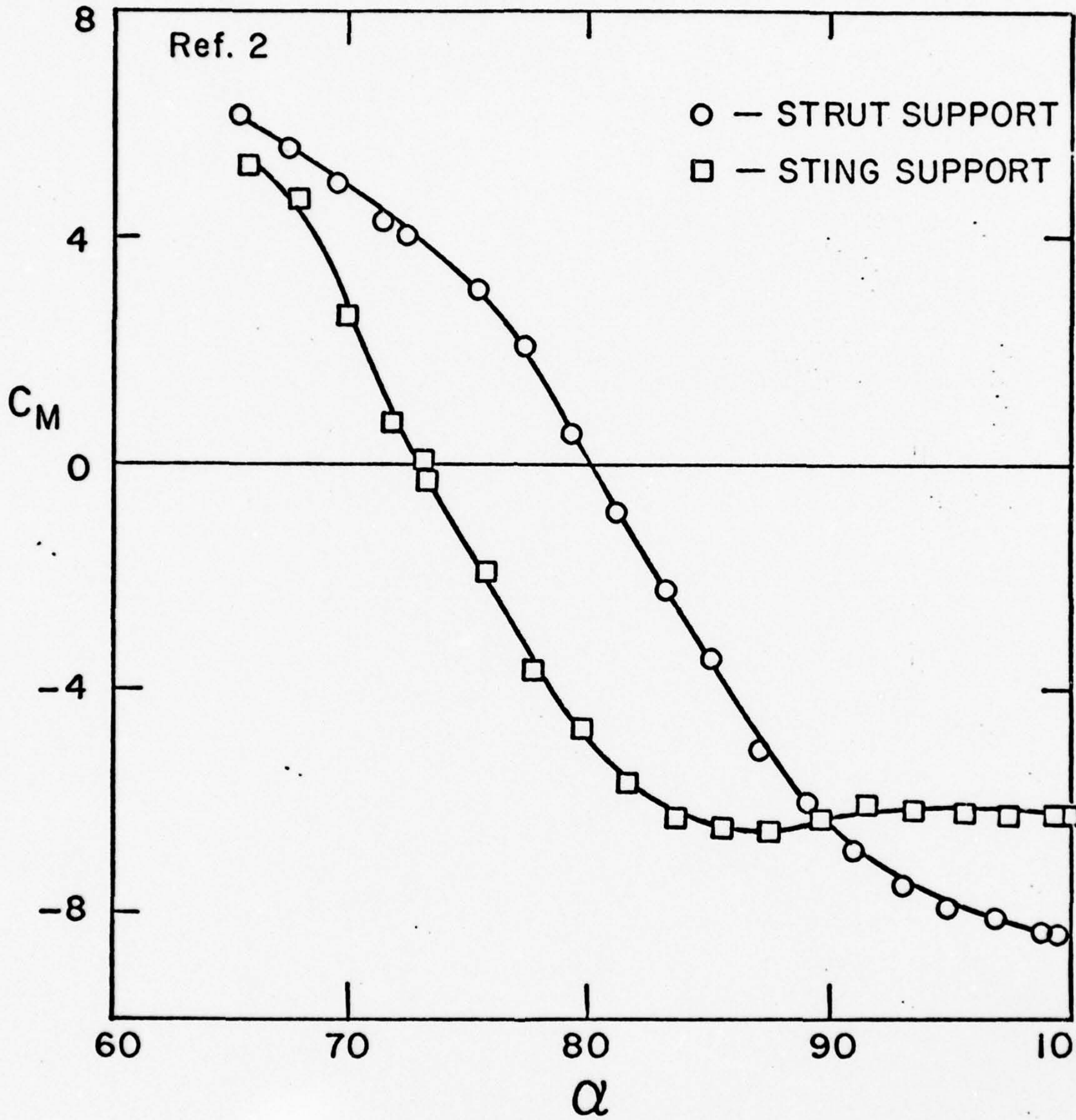
FIGURE I.



AN EXAMPLE OF SUPPORT INTERFERENCE ON THE NORMAL FORCE COEFFICIENT

$R_e = 2 \times 10^6 /ft$ $M_\infty = 0.6$

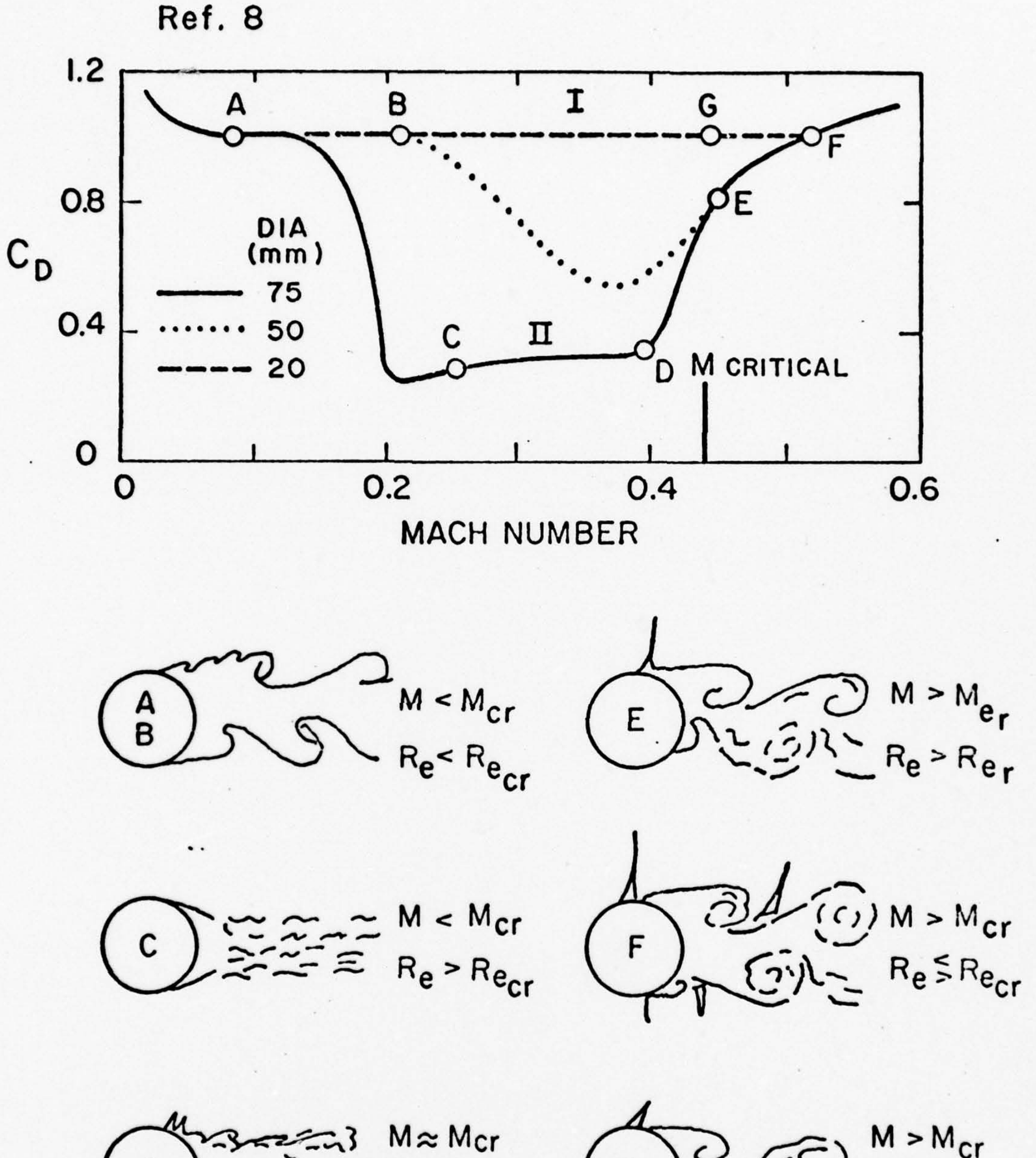
FIGURE 2.



AN EXAMPLE OF SUPPORT INTERFERENCE ON THE PITCHING MOMENT COEFFICIENT

$R_e = 2 \times 10^6 / ft$ $\quad M_\infty = 0.6$

FIGURE 3.



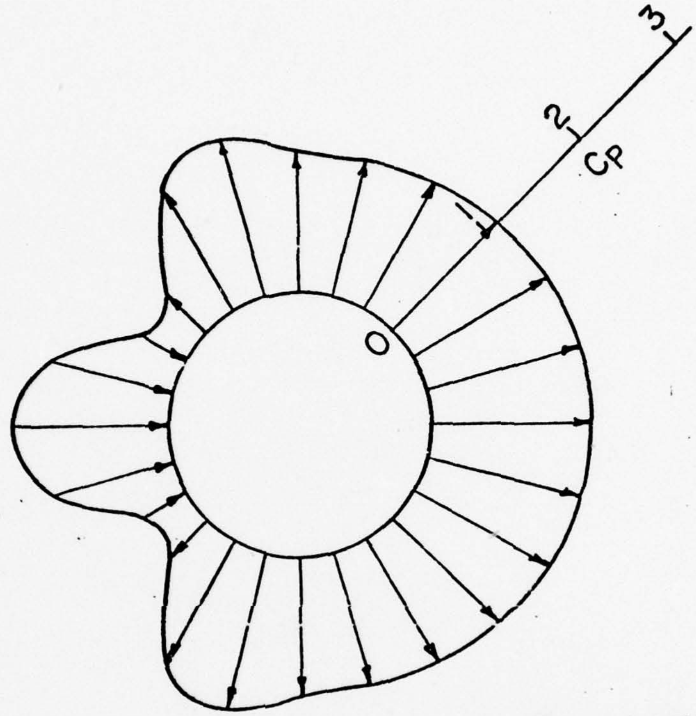
VARIATION OF DRAG COEFFICIENT AND WAKE PATTERNS WITH MACH AND REYNOLDS NUMBER

FIGURE 4.

a) M = 0.45, R_e = 203,000

FLOW AROUND A TWO DIMENSIONAL CYLINDER
AT THE CRITICAL MACH NUMBER (REF. 8)

FIGURE 5.



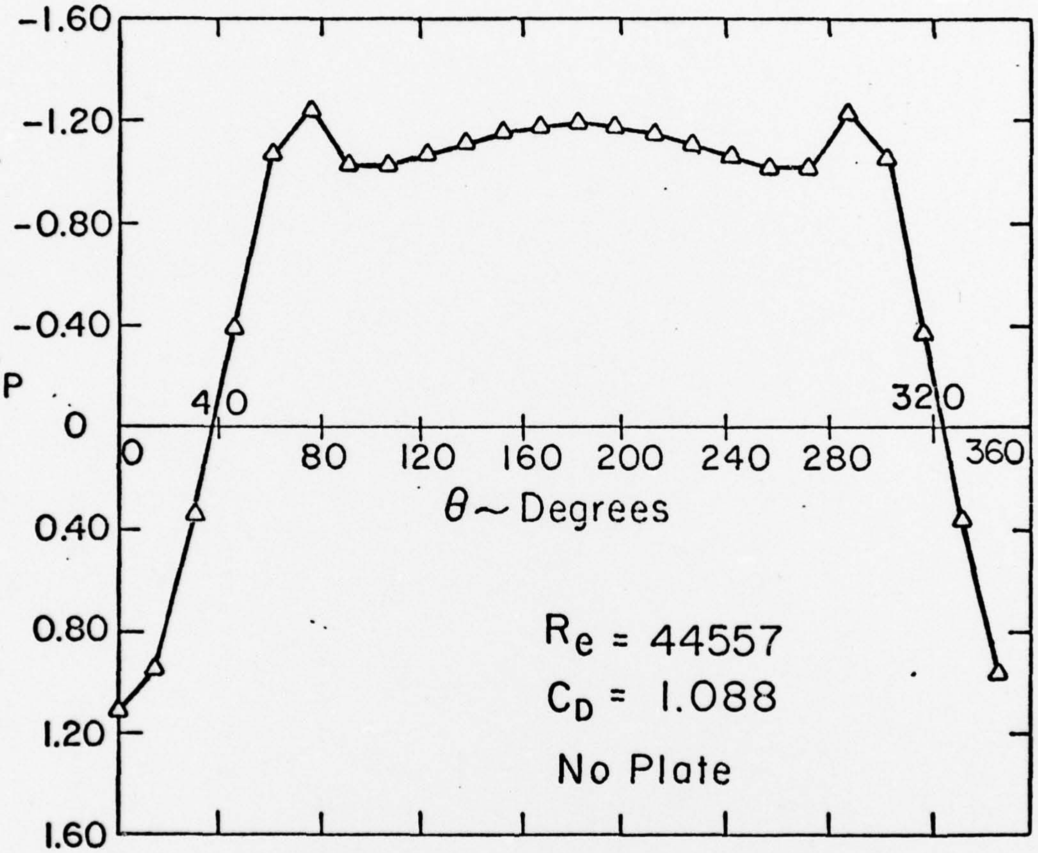
$R_e = 44557$

$C_D = 1.088$

NO PLATE

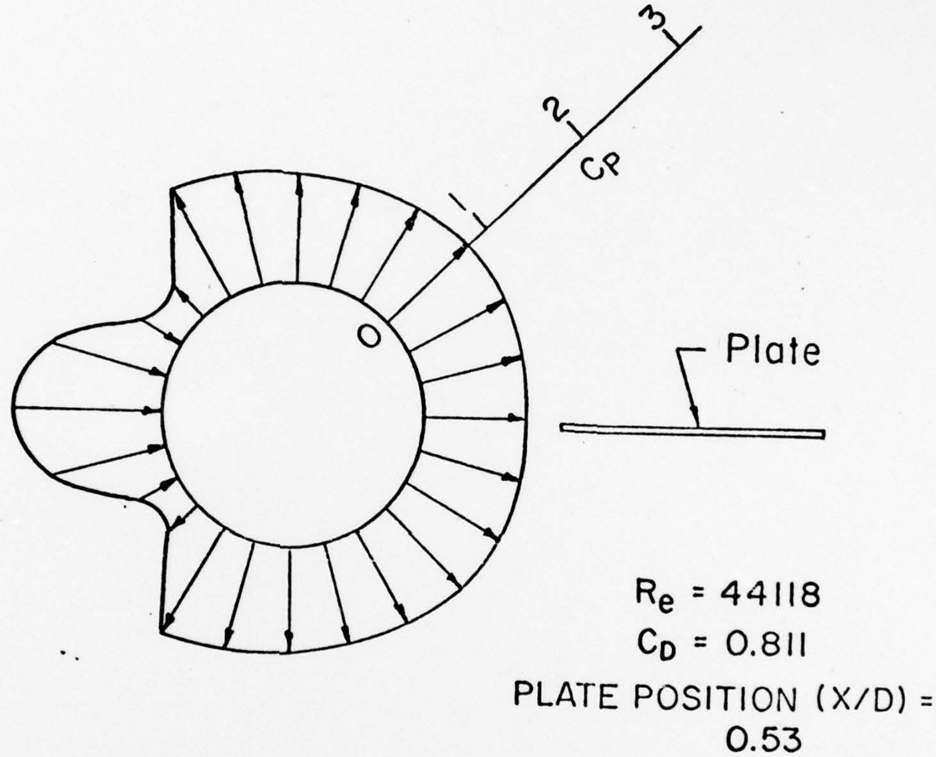
PRESSURE DISTRIBUTION AROUND THE CYLINDER WITHOUT A SPLITTER PLATE

FIGURE 6.



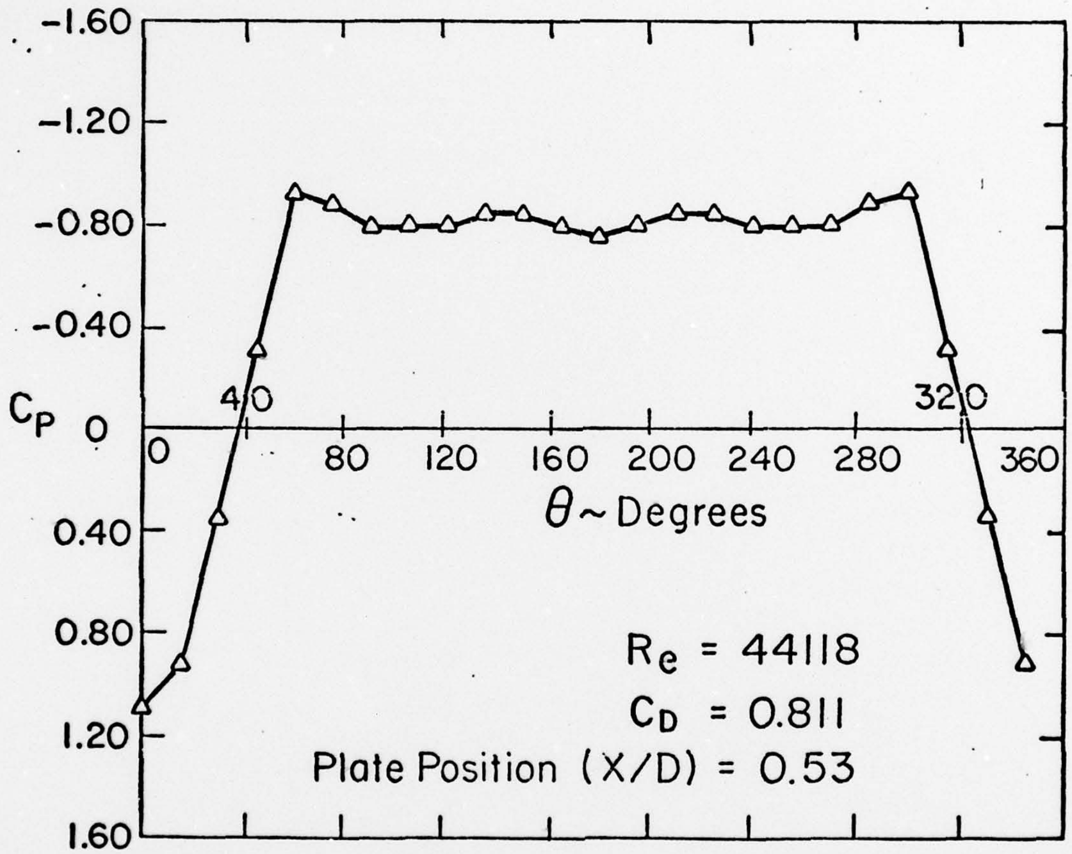
PRESSURE COEFFICIENT VERSUS ANGULAR POSITION — (NO PLATE)

FIGURE 7.



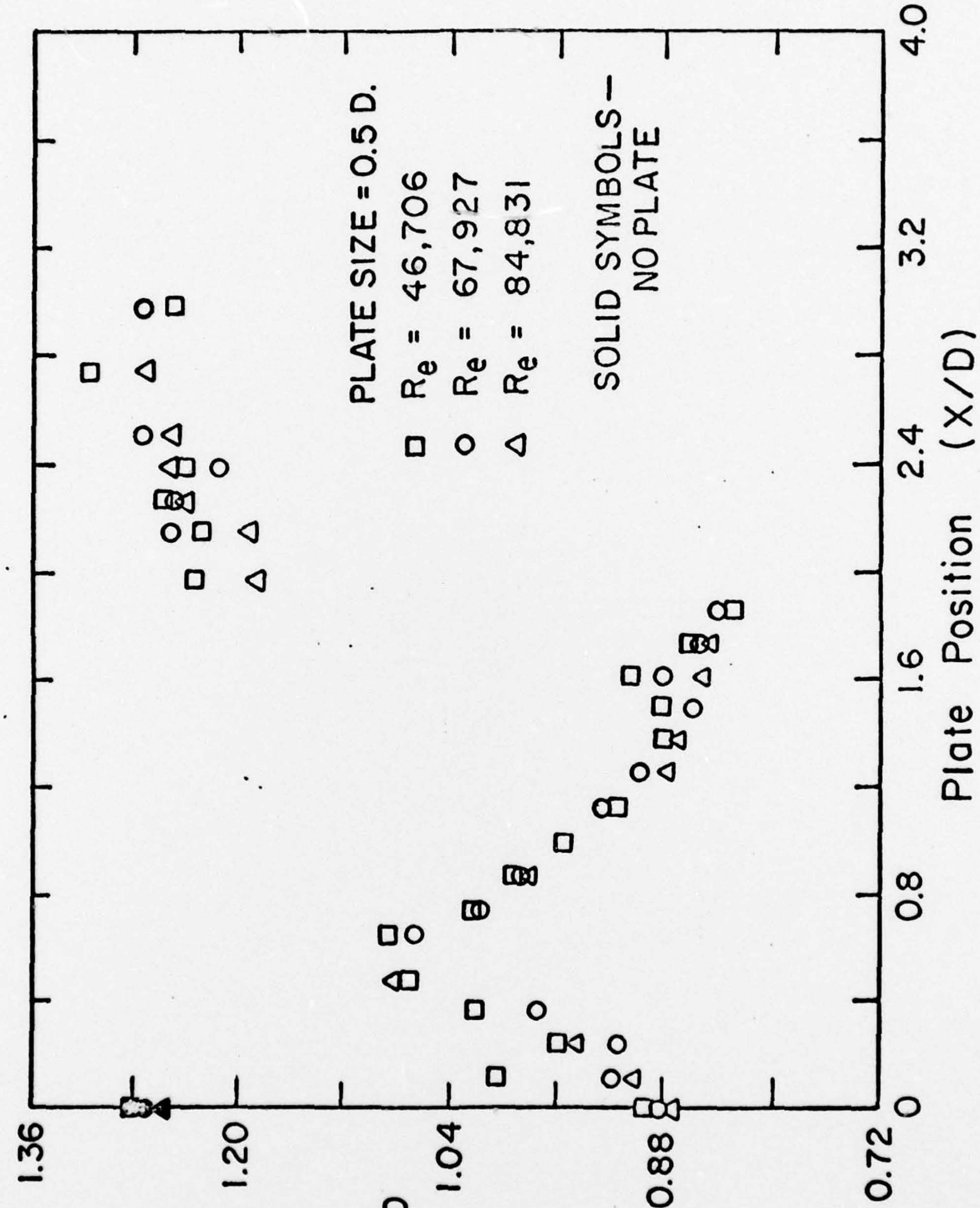
PRESSURE DISTRIBUTION AROUND THE CYLINDER WITH A WAKE SPLITTER PLATE

FIGURE 8.



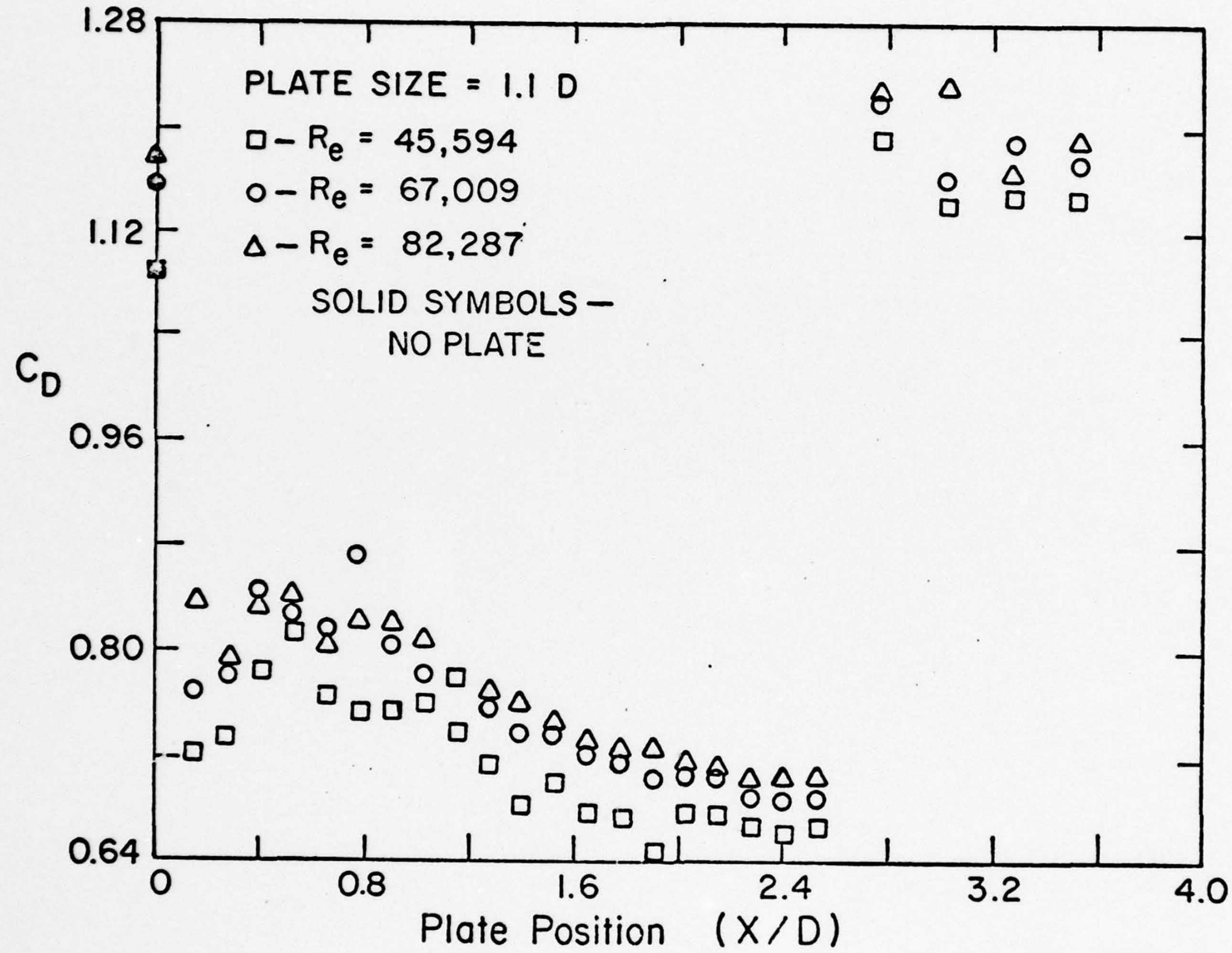
PRESSURE COEFFICIENT VERSUS ANGULAR POSITION – (WITH A SPLITTER PLATE)

FIGURE 9.



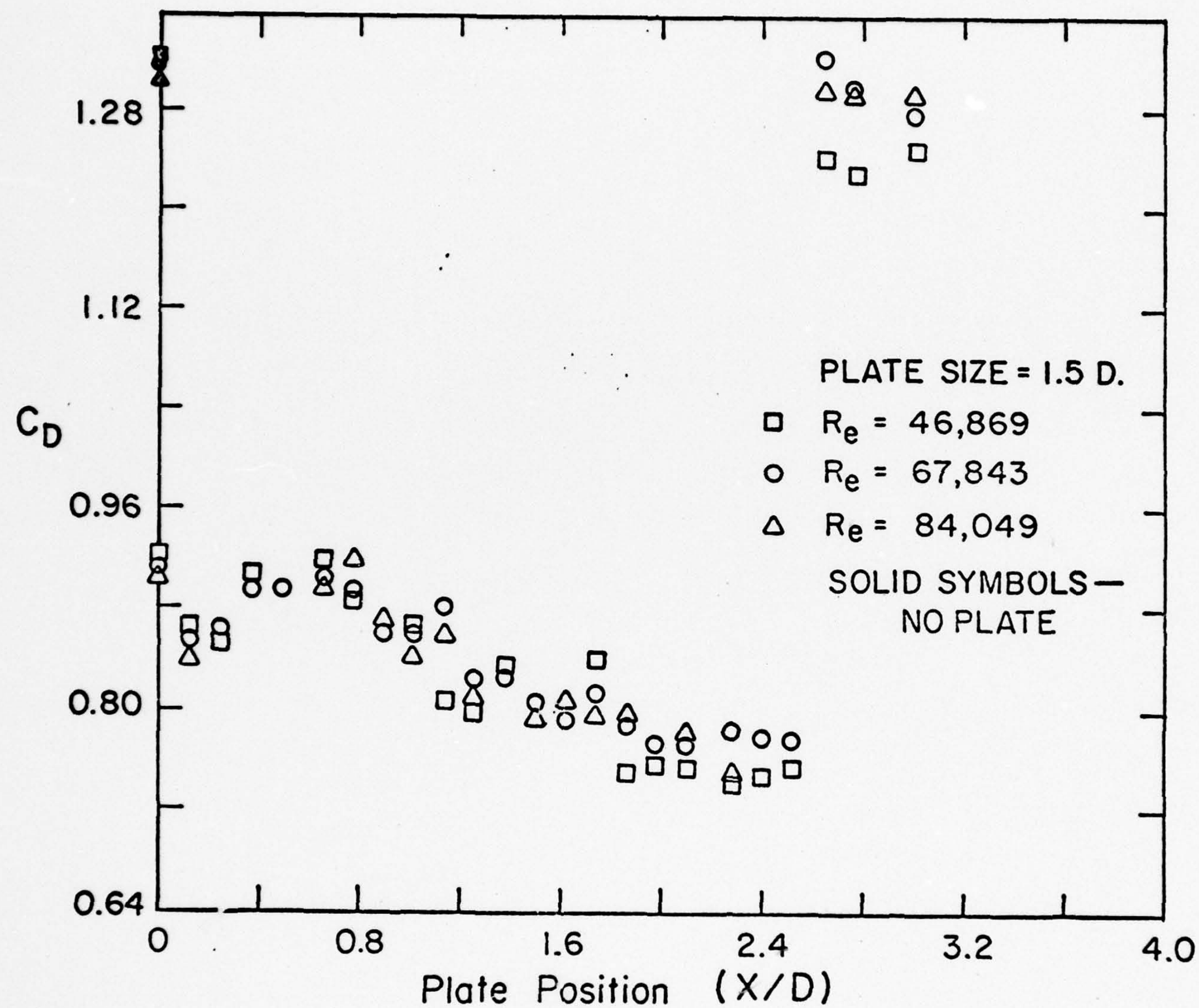
DRAG COEFFICIENT VERSUS PLATE POSITION

FIGURE 10.



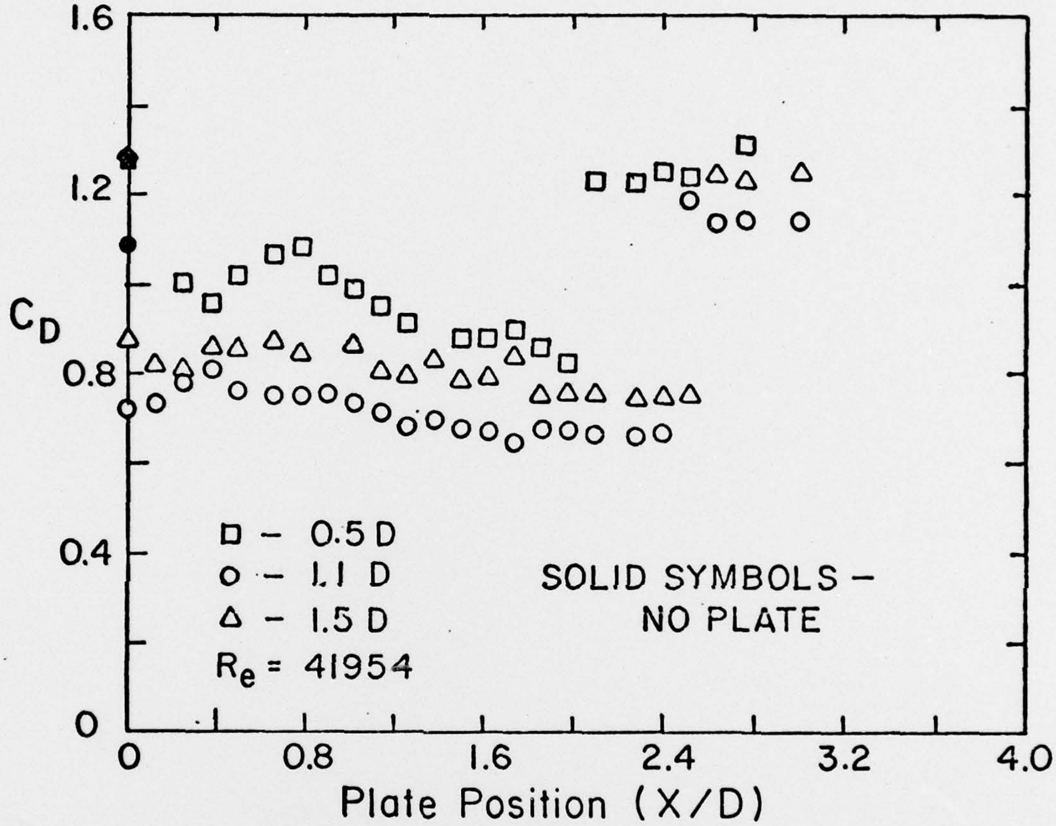
DRAG COEFFICIENT VERSUS PLATE POSITION

FIGURE 11.



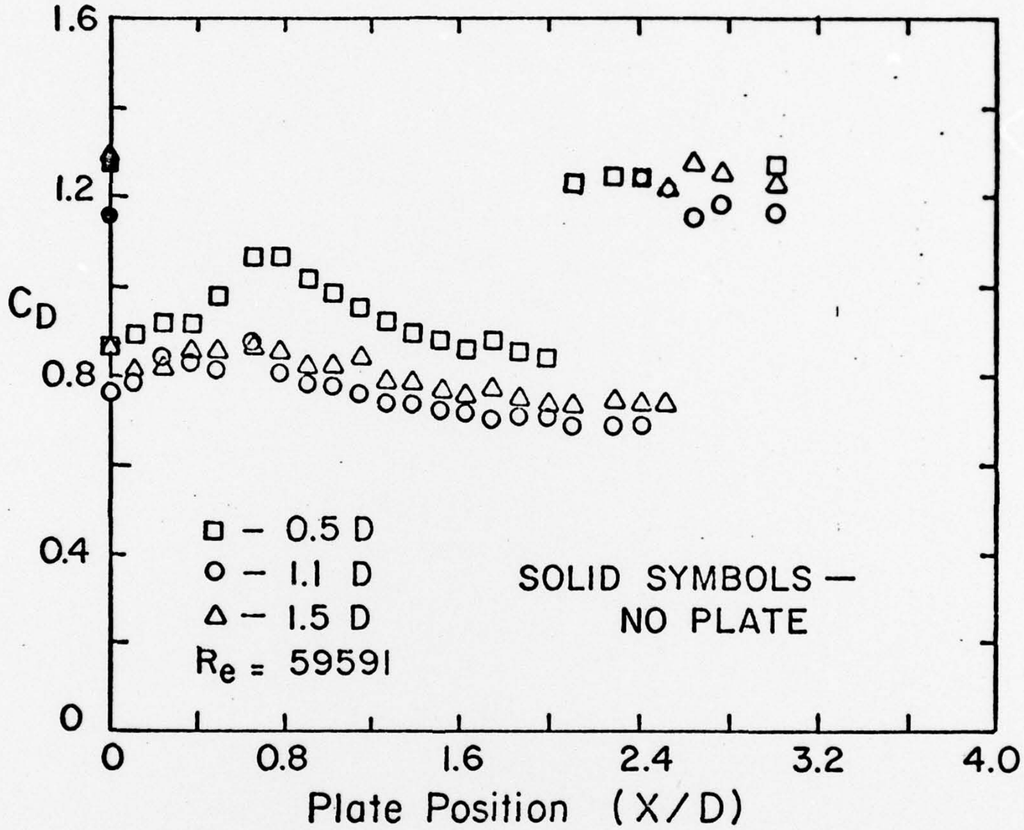
DRAG COEFFICIENT VERSUS PLATE POSITION

FIGURE 12



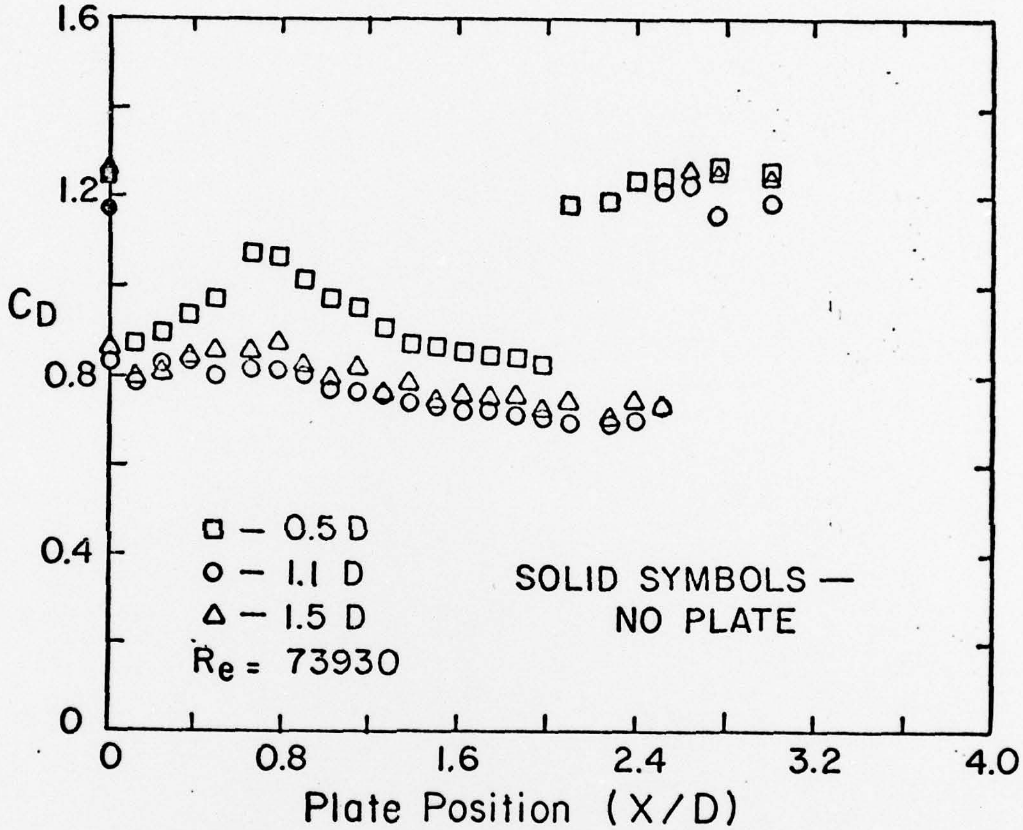
DRAG COEFFICIENT VERSUS PLATE POSITION
— VARYING PLATE SIZE R_e = 41,954

FIGURE 13.



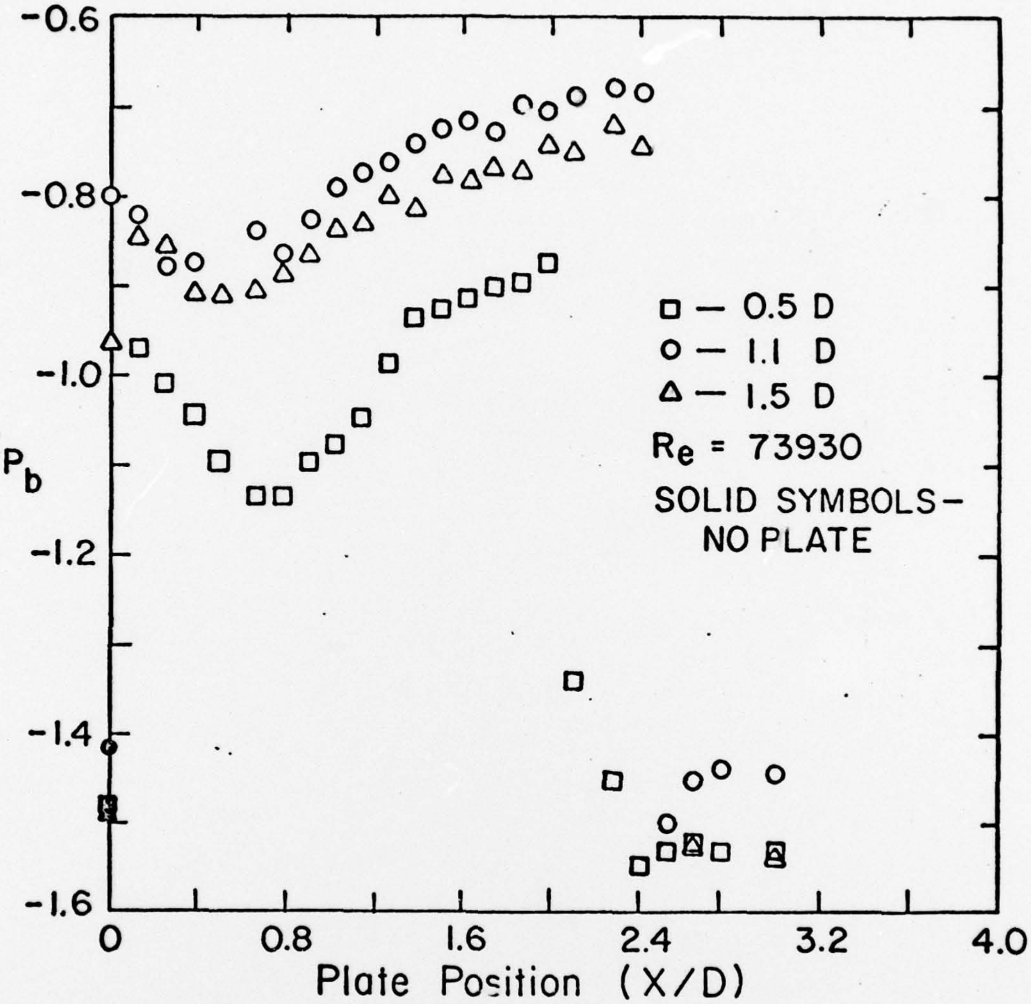
DRAG COEFFICIENT VERSUS PLATE POSITION — VARYING PLATE SIZE R_e = 59,591

FIGURE 14.



DRAG COEFFICIENT VERSUS PLATE POSITION — VARYING PLATE SIZE R_e = 73,930

FIGURE 15.

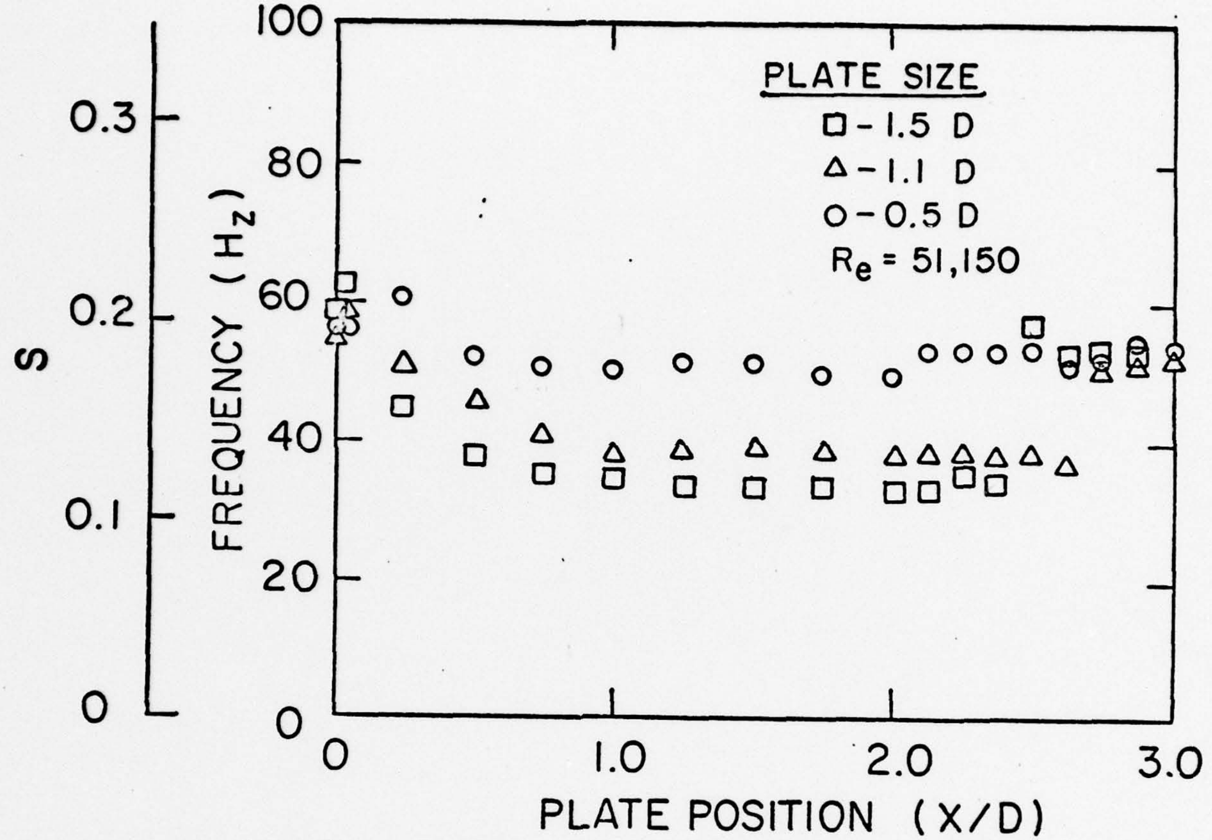


BASE PRESSURE COEFFICIENT

VS.

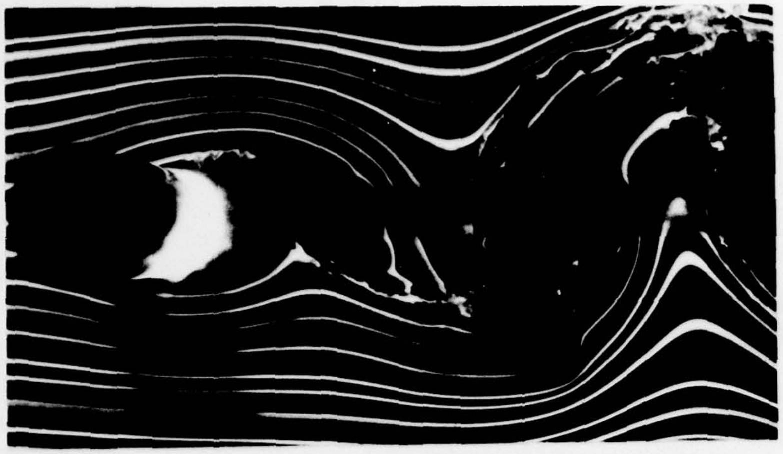
PLATE POSITION

FIGURE 16.



INFLUENCE OF SPLITTER PLATE ON VORTEX SHEDDING FREQUENCY

FIGURE 17.



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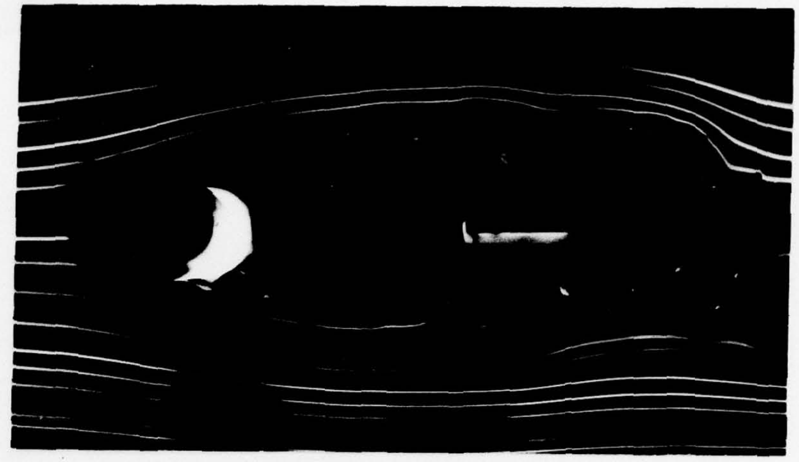

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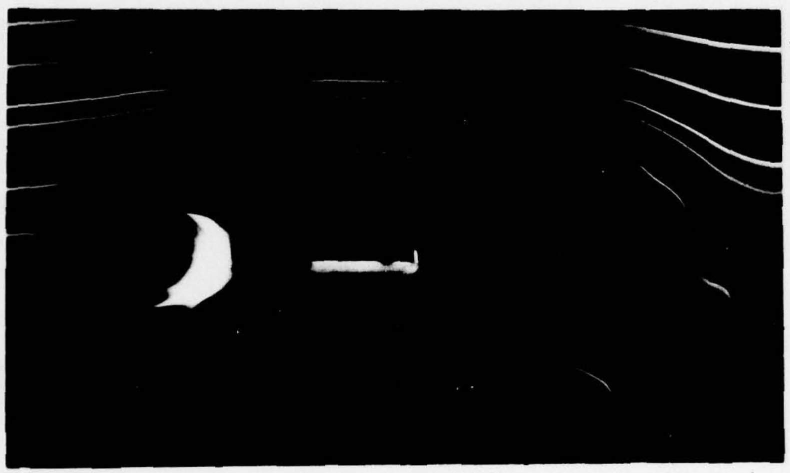

PLATE POSITION X/D = 1.0

PLATE POSITION X/D = 3.0

SMOKE PHOTOGRAPHS

FIGURE 18.

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18 19 **REPORT DOCUMENTATION PAGE**

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AERODYNAMIC INTERFERENCE
VORTEX WAKE
HIGH ANGLE OF ATTACK TESTING
CYLINDER-SPLITTER PLATE

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Results from an experimental investigation of strut support interference on high angle of attack aerodynamic measurements are presented. The influence of the strut support on the leeward wake structure was investigated by means of a two-dimensional experiment of a cylinder-splitter plate combination. Pressure distributions, pressure drag coefficient and wake flow visualization data for various cylinder-splitter plate combinations are presented for high subcritical Reynolds numbers. The influence of plate position and size on the pressure drag coefficient were also examined. The results show the splitter plate can alter

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